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Research paper

The inception of a Paleotethyan magmatic arc in Iberia

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ABSTRACT

This paper presents a compilation of recent U-Pb (zircon) ages of late Carboniferous–early Permian (LC–EP) calc-alkaline batholiths from Iberia, together with a petrogenetic interpretation of magma generation based on comparisons with Mesozoic and Tertiary Cordilleran batholiths and experimental melts. Zircon U-Pb ages distributed over the range ca. 315–280 Ma, indicate a linkage between calc-alkaline magmatism, Iberian orocline generation and Paleotethys subduction. It is also shown that Iberian LC–EP calc-alkaline batholiths present unequivocal subduction-related features comparable with typical Cordilleran batholiths of the Pacific Americas active margin, although geochemical features were partially obscured by local modifications of magmas at the level of emplacement by country rock assimilation. When and how LC–EP calc-alkaline batholiths formed in Iberia is then discussed, and a new and somewhat controversial interpretation for their sources and tectonic setting (plume-assisted relamination) is suggested. The batholiths are proposed to have formed during the subduction of the Paleotethys oceanic plate (Pangaea self-subduction) and, consequently, they are unrelated to Variscan collision. The origin of the Iberian batholiths is related to the Eurasian active margin and probably represents the inception of a Paleotethyan arc in the core of Pangaea.

1. Introduction

There is currently general consensus regarding global palaeogeographic views of Pangaea during late Carboniferous–early Permian times (LC–EP; ca. 315–280 Ma), which place Iberia at the core of this supercontinent, near the Eurasian active margin located to the east (Cocks and Torsvik, 2006; Stampfli and Kozur, 2006, and references therein). Surprisingly, in spite of this widely-accepted palaeogeographic proximity, the likely relationship between the source of Iberian LC–EP calc-alkaline magmas and the subduction of the Paleotethys oceanic plate has never been explored.

This point of view was first discussed in a general way for the Alpine arc (Finger and Steyrer, 1990) with regard to the Variscan granitoids of the Tauern area. But the existence of a wide magmatic province in the Alpine domain (Catalonia, Pyrenees, Calabria, Sardinia, Corsica, Provence, Tuscan nappes, Briançonnais domain, the southern and eastern Alps), characterized by the transition from LC–EP calc-alkaline plutonism to early to mid-Permian post-collisional or extension related magmatism was documented by Stampli (1996) and references therein. The inception of the subduction of Paleotethys in the Permian and a representation of subduction-related magmatic belts were later presented by Stampfli (2001).

Until now, LC–EP calc-alkaline magmas in Iberia have been linked by a number of researchers with a range of sources and tectonic settings associated with Variscan collision. Among these, are: (1) the reworking of different crustal protoliths, including metaigneous and metasedimentary rocks (Bea et al., 2003); (2) the reworking of oceanic metabasic rocks accreted to mid-to-lower crustal levels (Villaseca et al., 2009); (3) the involvement of mantle-derived melts or meta-igneous lower crust (Fernández Suárez et al., 2011); and (4) a primarily igneous rock source stemming from depleted mantle or meta-igneous lower crust and derived by partial melting of heterogeneous metasedimentary detrital rocks in the mid-crust (Neiva et al., 2009). Recently, a new tectonic model was presented for the origin of LC–EP calc-alkaline

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magmatism in Iberia (Gutierrez-Alonso et al., 2008, 2011; Fernández Suárez et al., 2011; Weil et al., 2012). According to this interpretation, mantle and lower-mid crust melting was triggered by lithosphere delamination coeval with the formation of the Iberian orocline. The proposed tectonic model suggests that closure of the Paleotethys Ocean was probably accommodated by unique Pangaea rotation and self-subduction during LC–EP times (e.g., Gutiérrez-Alonso et al., 2008). This permits a possible relationship between the development of the Eurasian active margin and magmatism occurring simultaneously in Iberia (Gutiérrez-Alonso et al., 2011).

Although many authors consider the LC–EP calc-alkaline magmatism to show geochemical characteristics demonstrably similar to magmas formed in subduction settings, this alternative interpretation of magma sources has never been considered in detail previously. Traditionally, the consensus has been that Iberian LC–EP calc-alkaline magmas are associated with the Variscan orogenic cycle ("late Variscan batholiths"), despite their being ca. 60–80 Ma younger than the subduction of the Rheic Ocean (ca. 385–365 Ma; Martinez-Catalan et al., 2007, 2009; Nance et al., 2010). A combination of factors have, in our view, precluded the satisfactory clarification of the sources and tectonic setting of ca. 315–280 Ma calc-alkaline magmatism in Iberia: (1) the scarcity of precise absolute ages for accurately determining the relationship between different calc-alkaline batholiths and the timing of deformation; (2) the lack of a robust petrogenetic model for explaining the origin of magmas and comparing them with other extensively studied examples of arc-related batholiths and corresponding petrologic and experimental constraints; and (3) the general acceptance of a single, consensual interpretation that supports the development of this calc-alkaline magmatic suite within the framework of the Variscan orogenic cycle. This paradigm disregards the wider context of the complex formation of Pangaea and the spatial proximity of Iberia relative to the Eurasian active margin during the LC–EP closing of the Paleotethys Ocean.

In this paper, an alternative interpretation is proposed for the source of the Iberian LC–EP calc-alkaline granitoids and mafic rocks within a subduction setting. In support of this new and controversial interpretation are the following data sets: (1) a compilation of recently published U-Pb (zircon) geochronology data obtained for the Iberian LC–EP calc-alkaline magmatism (Neiva et al., 2009; Fernández-Suárez et al., 2011; Díaz Alvarado et al., 2013; Pereira et al., 2014); and (2) a comparison of major compositional relations between the Iberian batholiths and the Cordilleran batholiths of North Patagonia (Castro et al., 2011) and those of eastern Peninsular Ranges (Lee et al., 2007), and with experimental residues and melts using a new robust model for simulating the generation of new crust in arcs (Castro et al., 2013). We conclude by examining the origin of ca. 315–280 Ma calc-alkaline batholiths in Iberia in relation to the Eurasian active margin and discuss whether the batholiths provide evidence for the inception of a Paleotethyan arc in the core of Pangaea.

2. Calc-alkaline Iberian batholiths: U-Pb zircon ages and compositions

The late Palaeozoic closure of the Rheic Ocean, following the collision of Gondwana and Laurussia, contributed to a mountain-building event during the formation of Pangaea (Variscan Orogen; Martinez-Catalan et al., 2007, 2009). Iberia, located in the western branch of the European Variscan belt, includes a ca. 1000 km-long magmatic province with a huge volume of LC–EP calc-alkaline batholiths extending from the Central-Iberian Zone to the southern Pyrenees (Fig. 1a). This calc-alkaline magmatic suite is dominated by I-type granodiorites with subordinate mafic rocks and S-type granites generated by crustal anatexis (Castro et al., 2002, 2003; Bea et al., 2003; Neiva et al., 2009; Villaseca et al., 2009; Fernández-Suárez et al., 2011; Diaz Alvarado et al., 2013). These calc-alkaline batholiths intruded Neoproterozoic to early Palaeozoic sedimentary successions that are dominated by detrital rocks with associated minor igneous bodies.

A compilation of recently published U-Pb geochronology data from Iberian LC–EP batholiths is presented in Table 1. The U-Pb (zircon) data show that calc-alkaline magmatism occurred in Iberia over an extended period of ca. 35 million years (LC–EP; Table 1; Fig. 1b). In Iberia, three main phases of Variscan deformation are described, which enable different magmatic suites to be distinguished (e.g., Castro et al., 2002; Dias et al., 2002; Martinez-Catalan et al., 2007; Fernández-Suárez et al., 2011; Gutierrez-Alonso et al., 2011; Diaz Alvarado et al., 2013). In accordance with this classification, LC–EP magmatic suites have been described as syn-D_3 and post-D_3 ("late Variscan") because they show sharp intrusive contacts with previous Variscan structures (D_1 and D_2 deformation phases). D_1 structures are related to the Variscan collision and the emplacement of allochthonous units (ca. 365–345 Ma; Escuder Viruete et al., 1994; Dallmeyer et al., 1997; Rubio Pascual et al., 2013), while D_2 structures are linked to Variscan extensional collapse and widespread crustal anatexis (ca. 345–320 Ma; Escuder Viruete et al., 1994; Dallmeyer et al., 1997; Martínez Catalán et al., 2004; Castiñeiras et al., 2008; Pereira et al., 2012a,b; Rubio Pascual et al., 2013), after cessation of Rheic subduction. Lower Carboniferous (LC) calc-alkaline intrusive bodies coeval with D_2 have been interpreted as coming from a mantle-derived magma that interacted, in different degrees, with crustal melts (Dias et al., 1998; Montero et al., 2004; Romeo et al., 2006; Moita et al., 2009; Pereira et al., 2009; Lima et al., 2011). Younger Variscan structures (D_3 deformation phase) are associated with the formation of the Iberian orocline (ca. 320–300 Ma; Gutierrez-Alonso et al., 2008, 2011; Pereira et al., 2012a).

The geochemical composition of Iberian LC–EP batholiths is summarized in Fig. 2. The ca. 315–280 Ma magmatic series from Iberia are divided into (Castro et al., 2002, and references therein): (1) a silicic ($SiO_2 > 53$ wt.%) calc-alkaline (I-type) series forming large batholiths with predominantly granodiorite composition; (2) a mafic rock association (diorite-gabbro) that occurs both in peri-batholithic massifs near the main contacts of the large granodiorite intrusions and intruding into migmatitic complexes; and (3) a peraluminous leucogranite (S-type) series, commonly associated with *in situ* migmatization. Fig. 2 includes geochemical diagrams (major elements) showing essential variations of representative Iberian LC–EP granitoids and mafic rocks (ca. 315–280 Ma). Iberian LC–EP granitoids are well grouped along curved trends characteristic of Cordilleran batholiths (Fig. 2a). Mafic rocks are partly cumulates formed as part of the calc-alkaline differentiation trend, and are partly derived from wet basaltic magmas (appinites) that are commonly associated with the Iberian batholiths, and show characteristic and unequivocal arc geochemical signatures (Castro et al., 2003) (Fig. 2a). The variation of the molar $Mg^{\#}$ shows a plateau region for rocks within the silica range 60–70 wt.%, which is a characteristic feature of Cordilleran granitoid batholiths (for example, Patagonian batholiths: Pankhurst et al., 1999; Hervé et al., 2007; Castro et al., 2011; and Sierra Nevada and Peninsular Ranges batholiths: Lee et al., 2007) (Fig. 2b). The continuous linear increase of the molar K ratio with decreasing MgO is also characteristic of calc-alkaline magma fractionation from a parental diorite precursor (Fig. 2c). An increase in aluminosity (A parameter: de la Roche, 1978; Debon and Le Fort, 1983) with fractionation is a characteristic feature of calc-alkaline (cafemic) trends (Fig. 2d). In all diagrams shown, the effects of the assimilation of local country rock (pelitic

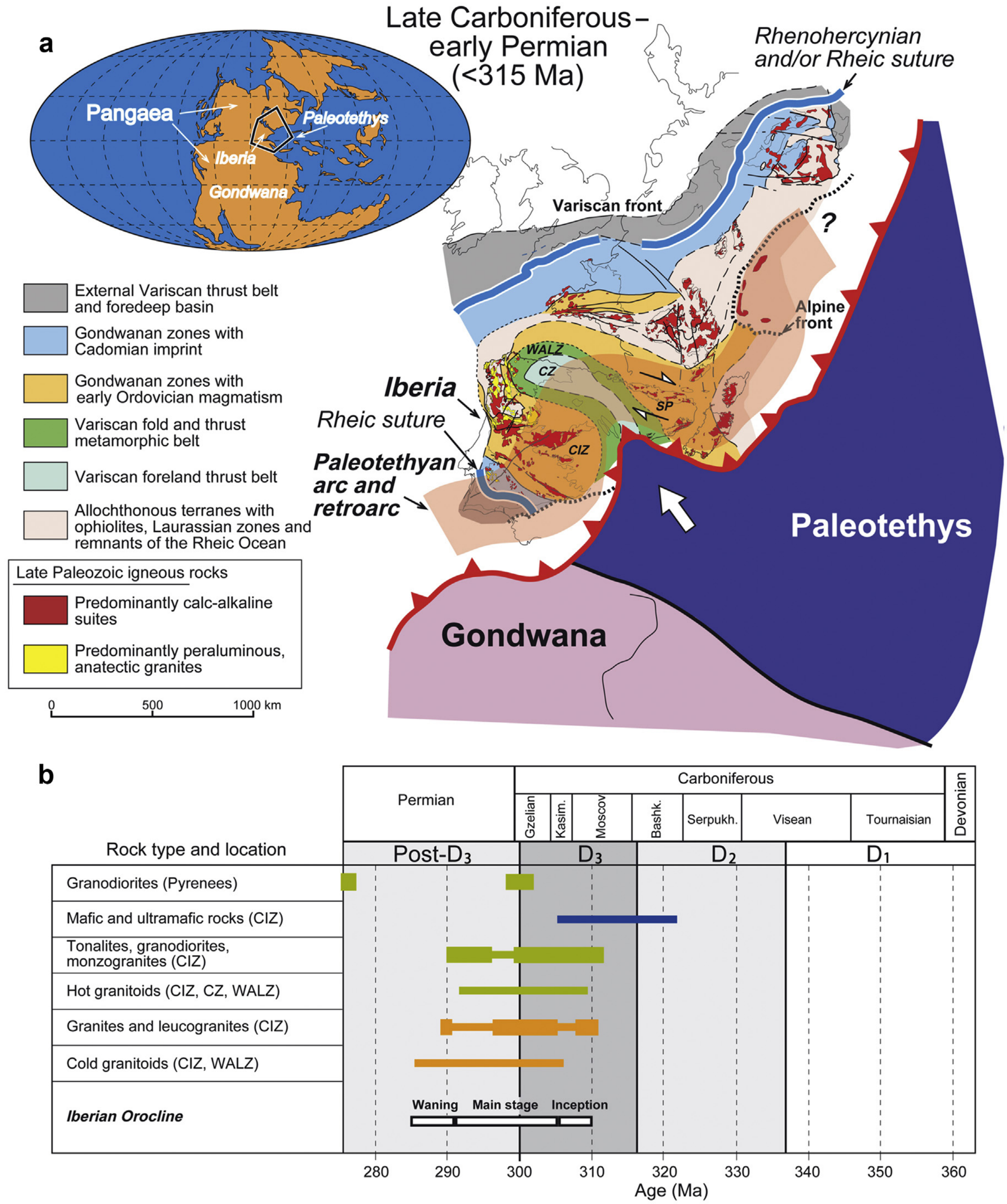

Figure 1. (a) Reconstruction of the Variscan belt at ca. 300 Ma (Gzhelian, latest Carboniferous), after the closing of the Rheic (or Rheno-Hercynian) Ocean and before the end of subduction at the western corner of the Paleotethys Ocean. Note that while some authors consider the location of the Rheic suture to be as indicated on this map (Linnemann et al., 2007; Faure et al., 2010; Nance et al., 2010; Kroner and Romer, 2013), others advocate the existence of the Rheno-Hercynian suture in Central Europe (Stampfli et al., 2011, 2013; von Raumer et al., 2012). The large white arrow marks the approximate direction of convergence between the Paleotethys oceanic lithosphere and the southern limit of the Variscan realm. Local segments of oblique convergence are responsible for the predominance of strike-slip tectonic regimes like the coeval dextral transpression described in southern Pyrenees (Druguet et al., 2014). Inset shows the location of the enlarged area in the east-central part of Pangaea. Adapted from Stampfli and Kozur, 2006; Stampfli et al., 2011, 2013; Pereira et al., 2014 and references therein. Trace of Variscan structures bent by the Iberian orocline modified from Martinez-Catalan et al. (2007) and Martínez Catalán (2011). (b) Diagram showing the age variation and time relations of LC–EP tectonic processes, D_3 Variscan deformation and granitoid/mafic rock generation in Iberia (Gondwanan zones with early Ordovician magmatism, CIZ–Central Iberian Zone and SP–Southern Pyrenees; Variscan fold and thrust metamorphic belt, WALZ–West-Asturian Leonese Zone; Variscan foreland thrust belt, CZ–Cantabrian Zone). Adapted from Gutierrez-Alonso et al. (2011) and Diaz Alvarado et al. (2013) and references therein; see Table 1 for references.

metasediments) are displayed. Contaminated samples depart from cotectic trends and point to the composition of pelitic migmatites. In Fig. 2e, most rocks of the Iberian LC–EP calc-alkaline magmatic series plot close to experimental cotectic lines, preferentially close to the low pressure and moderate water cotectic liquids (thick dashed line: Sisson et al., 2005; Castro, 2013). Several samples tend to deviate from the cotectic line due to the local effects of pelitic rock assimilation (Díaz Alvarado et al., 2011).

Table 1
Compilation of LC–EP calc-alkaline Iberian batholith ages (ca. 315–280 Ma).

Rocks	Location	Age (Ma)	Method	Author
Bt granodiorites	CIZ (Gredos)	312	U/Pb zrn, SHRIMP	Díaz Alvarado et al., 2013
Granodiorites	CIZ (Castelo Branco)	309	U/Pb zrn ID-TIMS	Antunes et al., 2010
Tonalites, gabbros	CIZ (Arges, Toledo, Guajaraz)	308–311	U/Pb zrn, Cameca IMS270	Bea et al., 2006
Bt ± Amph granodiorites	CIZ (Los Pedroches)	308	U/Pb zrn ID-TIMS	Carracedo et al., 2009
Peraluminous granites	CIZ (Casal Vasco, Junqueira)	308–311	U/Pb zrn, mnz ID-TIMS	Valle Aguado et al., 2005
Monzogranites	CIZ (Cota)	307	U/Pb zrn, mnz ID-TIMS	Valle Aguado et al., 2005
Bt granites and Crd granites	CIZ (Béjar)	307	U/Pb zrn, SHRIMP	Zeck et al., 2007
Granitoids	CIZ (Gredos)	307	U/Pb zrn, SHRIMP	Díaz Alvarado et al., 2013
Bt monzogranites	CIZ (Berlengas island)	307	U/Pb zrn ID-TIMS	Valverde-Vaquero et al., 2011
Monzogranite	CIZ-OMZ (Nisa)	307–309	U/Pb zrn, SHRIMP	Solá et al., 2009
Granites	CIZ (Gouveia)	307–310	U/Pb zrn ID-TIMS	Neiva et al., 2012
Mafic and ultramafic rocks	CIZ (Gredos)	307–322	$^{207}Pb/^{206}Pb$ zrn, ID-TIMS	Montero et al., 2004
Bt monzogranites	CIZ (Braga-Celeirós)	306–311	U/Pb zrn, mnz ID-TIMS	Dias et al., 1998
Mafic rocks	CIZ (Toledo, La Bastida)	306–311	Cameca IMS270	Bea et al., 2006
Tonalite	CIZ-OMZ (Aldeia da Mata)	306	U/Pb zrn, SHRIMP	Solá et al., 2009
Gabbro and norites	CIZ (Béjar)	306	U/Pb zrn, SHRIMP	Zeck et al., 2007
Leucogranites	CIZ (Gredos)	305	U/Pb zrn, SHRIMP	Díaz-Alvarado et al., 2013
Leucogranites	CIZ (Cerro Mogábar)	304	U/Pb zrn, ID-TIMS	Carracedo et al., 2008
Crd monzogranite	CIZ (Gredos)	304	U/Pb zrn, SHRIMP	Díaz Alvarado et al., 2013
Migmatitic hornfelses	CIZ (Gredos)	303	U/Pb zrn, SHRIMP	Díaz Alvarado et al., 2013
Granites and leucogranites	CIZ (La Cabrera)	302	$^{207}Pb/^{206}Pb$ zrn, ID-TIMS	Casquet et al., 2004
Two-mica monzogranites	CIZ (Gouveia)	302	U-Th-Pb mnz, SHRIMP	Neiva et al., 2009
Leucogranites	CIZ (Briteiros)	300	U/Pb zrn, mnz ID-TIMS	Dias et al., 1998
Bt monzogranites	CIZ (Vila Pouca de Aguiar)	299	U/Pb zrn, ID-TIMS	Martins et al., 2009
Quartz diorite	E-Pyrenees (Cap Creus-Tudela)	299	U/Pb zrn, SHRIMP	Druguet et al., 2014
Granodiorites	S-Pyrenees (Boí, Montellá)	299–301	U/Pb zrn, SHRIMP	Pereira et al., 2014
Cold-granitoids	CIZ	299	U/Pb zrn, LA-ICPMS	Gutierrez-Alonso et al., 2011
Granites	CIZ (Gouveia)	297	U/Pb zrn ID-TIMS	Neiva et al., 2012
Granites	CIZ (Gouveia)	297–304	U/Pb mnz ID-TIMS	Neiva et al., 2012
Hot-granitoids	CIZ-CZ-WALZ	292–309	U/Pb zrn, LA-ICPMS/ID-TIMS	Gutierrez-Alonso et al., 2011 and references therein
Two-mica monzogranite	CIZ (La Cabrera)	292	U/Pb zrn, ID-TIMS	Valverde-Vaquero et al., 1997
Granodiorite	E-Pyrennes (Roses)	291	U/Pb zrc, SHRIMP	Druguet et al., 2014
Bt granites	CIZ (Gerês-Peneda)	290–296	U/Pb zrn, mnz, ID-TIMS	Dias et al., 1998
Leucogranite	CIZ (Gouveiras)	289	U-Th-Pb mnz, SHRIMP	Neiva et al., 2009
Cold-granitoids	CIZ-WALZ	286–306	U/Pb zrn, LA-ICPMS/ID-TIMS	Gutierrez-Alonso et al., 2011 and references therein
Granodiorites	S-Pyrenees (Vielha)	276	U/Pb zrn, SHRIMP	Pereira et al., 2014

3. Discussion

The generation of Iberian LC–EP calc-alkaline batholiths in a tectonic setting distinct from subduction, conflicts with essential thermal requirements and phase equilibria constraints on magma generation and fractionation. Moreover, the generation of these large batholiths in response to a supposed late-Variscan extension is incompatible with the overall calc-alkaline affinity of the magmas.

It is broadly recognized that granitic rocks of extensional (e.g., back-arc) settings are of alkaline affinity (A-type), with strong Fe enrichment, high Na/K ratios and typically meta-aluminous features (Eby, 1990). The chemical composition of the Iberian LC–EP calc-alkaline batholiths, however, is distinct from that of the Permian to Cretaceous NE China batholiths with granitic rocks of A-type and transitional I-type to A-type affinities that formed in one of the world's most outstanding areas of lithospheric extension (Wu et al., 2002, 2005).

The Iberian LC–EP calc-alkaline batholiths also display transitions to locally-formed anatectic granites (S-type). It is known that the greater or lesser presence of associated S-type granites largely depends on the level of emplacement and the more or less fertile composition of the crustal lithologies hosting the calc-alkaline batholiths. For example, S-types granites are scarce or absent in large regions of the Patagonian batholiths in South America where rocks hosting the intrusions are mostly volcanics. However, S-type granites are present, and transitions from I-type to S-type are common in other Cordilleran-type batholiths, for example the pre-collisional S-type granites of the Lhasa terrane as part of the calc-alkaline Gangdese batholith (Zhang et al., 2013), and the anatectic granites from the Famatina arc system associated with the Gondwana active margin in Argentina (Grosse et al., 2011). In the case of Iberia, the emplacement of the LC–EP calc-alkaline batholiths into a fertile middle crustal level dominated by a several kilometer-thick sequence of Neoproterozoic greywackes is the reason for extensive anatexis over large regions close to the intrusion contacts. Migmatites are common at the contacts, with anatectic granites showing the same age as the intruding magma (e.g., Refugio del Rey leucogranite and Gredos granodiorites; Díaz Alvarado et al., 2013). The interaction between the intrusive granodiorites and the fertile metasedimentary host gave rise to mechanical interactions between the magma and partially molten host, leading to local hybridization of the intrusive magma, which becomes more peraluminous and more potassic. Criteria for identifying these local processes have been determined by means of combined geochemical and experimental studies (Díaz Alvarado et al., 2011).

The ultimate origin of the granodiorite magmas in relation to subduction is a problem of general scope that has been widely discussed in previous papers. The lower crust is often cited as the source of calc-alkaline batholiths, either for those closely related to recognizable active margins, or those apparently unrelated to coeval subduction.

The lower crust interpretation is based on two important observations: (1) many batholiths are intrusive into the middle crust at pressures ranging from 4 to 8 kbar; and (2) melts produced from the mantle underlying the continental crust must be basaltic. A two-step process consisting of the melting of mantle-derived basaltic rocks previously underplated in the lower crust has been proposed (Petford and Atherton, 1996; Petford and Gallagher, 2001; Hawkesworth and Kemp, 2006). Plume-assisted relamination is a new concept in subduction-related magmatism emerging from a variety of independent approaches: (1) thermomechanical numerical experiments (Gerya et al., 2004; Gerya and Meilick, 2011; Vogt et al., 2012); (2) experimental phase equilibria of batholith-forming magmas (Castro et al., 2010; Castro, 2013, 2014); and (3) mass balance calculations (Hacker et al., 2011). Essentially, the concept involves the generation of magmas of intermediate composition (andesite-diorite) by the melting of subducted materials in silicic composite plumes (composed of oceanic crust and sediments) which are finally relaminated at a level below the lower crust, where they split by means of melt segregation into liquids that are emplaced into the middle and upper crust (batholiths) and residues that remain in the lower crust (mafic granulites). Relaminated andesite magmas may reach the lower continental crust at high temperatures of about 1000 to 1100 °C, containing a crystal proportion of about 50% according to predictions from phase equilibrium experiments. Temperatures of the same order (ca. 1000 °C) are recorded by lower crust granulite xenoliths around the world (for example, Paso de Indios xenoliths; Castro et al., 2011, 2013, and references therein). Furthermore, the characteristic low-water content of calc-alkaline batholiths, with an initial water content of about 1–2 wt.% H_2O, is compatible with high temperatures of about 1000 °C at the time of magma segregation from composite underplated plumes.

In the case of the Iberian LC–EP calc-alkaline granitoids, which have been considered to be unrelated to coeval subduction (the Rheic Ocean had closed ca. 60–80 Ma earlier: e.g., Martinez-Catalan et al., 2007, 2009; Pereira et al., 2012b), the lower crust is often cited as their source. In our view, several factors indicate an extra-crustal origin for the Iberian LC–EP calc-alkaline magmas, suggesting a link to a subduction setting similar to that of the Cordilleran batholiths formed during the Mesozoic and Tertiary at the Pacific active margin of the Americas (e.g., Sierra Nevada: Lee et al., 2006, 2007, and Patagonia: Pankhurst et al., 1999; Parada et al., 1999; Herve et al., 2007; Castro et al., 2011). A detailed discussion of the arguments supporting an off-crust generation of calc-alkaline batholiths is provided in other papers (e.g., Castro et al., 2010, 2013; Castro, 2014).

We have shown that the I-type granodiorites forming the Iberian LC–EP batholiths have the features of calc-alkaline silicic magmatism characteristic of active continental margins like the Andes (Patagonian batholith) and the North American Cordillera (Sierra Nevada batholith). Another unequivocal sign of a subduction setting is the occurrence of mafic rocks (appinites). These represent calc-alkaline mafic systems with typical arc signatures (Murphy, 2013). They resemble the geochemical signature of high-Mg andesites (HMA) and sanukitoids, formed by the reaction of subduction-derived melts with the overlying mantle (Kelemen et al., 2003). However, the possibility that they were alkaline hydrous magmas enriched with crustal components by contamination from country rocks has been suggested for particular cases (Scarrow et al., 2009). The problem here relates to classical discussion on the origin of the crustal signatures of arc magmas as acquired by either: (1) the assimilation of lower crust materials by basaltic magmas (Hildreth and Moorbath, 1988); or (2) the incorporation of crustal components (including sedimentary rocks) into the mantle source of magmas through subduction erosion (Stern, 1991). The former (crustal contamination) may be disregarded on the basis of simple mass balance calculations because the preserved basaltic nature of magmas would have been destroyed by silica enrichment associated with assimilation or magma mixing (Castro et al., 2003). The latter implies that crustal signatures originated in a metasomatized mantle source or through the reaction between melts from the subduction zone and the overlying peridotite mantle (Kelemen et al., 2003). The relationships between these subduction-related mafic rocks and large Iberian LC–EP calc-alkaline batholiths are crucial for providing an understanding of their origins. I-type granodiorites represent silicic magmas, possibly derived by fractionation from a diorite (andesite) precursor that could not have been generated by melting the lower crust, or through the melting of a metasomatized mantle. It has recently been proposed that the origin of these subduction-related mafic rocks is associated with plume-assisted relamination (Vogt et al., 2012; Castro et al., 2013) as part of a new paradigm for magma generation in the supra-subduction mantle wedge (Gerya et al., 2004).

We realize, however, that the onset of magmatism related to Paleotethys subduction (Eo-Cimmerian cycle) may have overlapped late-magmatic Variscan events (Druguet et al., 2014; Pereira et al., 2014). It is possible that some Iberian LC–EP magmatic events took place in the transition from the end of Variscan collision to the continuing subduction of the Paleotethys active margin. With the available chronological and geochemical data it is difficult to unequivocally trace the boundary between these two magmatic events of different origin. A detailed geochronology and geochemistry study of the wet-basaltic (normally shoshonitic) magmatism that is present in Iberia may reveal important clues on this problem.

In summary, the use of a robust petrogenetic model for explaining the origin of magmas, and a comparison with other extensively studied examples of arc-related batholiths, was essential for deciphering the subduction-related geochemical signatures of the Iberian magmas that were partially obscured by local modifications of the magmas at the level of emplacement. The presence of several km-thick sequences of Ediacaran and Cambrian detrital Al-rich sedimentary host rocks explains the widespread geochemical modifications of the intruding magmas, which underwent local assimilation and conversion to hybrid cordierite monzogranites. The late generation of S-type peraluminous leucogranites is related to the local thermal effects of the intruding batholiths.

The compilation of recent geochronology U-Pb (zircon) data provides conclusive evidence that precludes a genetic connection between Iberian LC–EP calc-alkaline magmatism and Variscan collision. The period during which calc-alkaline magmatism was generated (ca. 315–280 Ma) coincides with the development of the Iberian orocline (Gutiérrez-Alonso et al., 2008; Fernández-Suárez et al., 2011; Weil et al., 2012; Johnston et al., 2013). Therefore, orocline formation and Pangaea self-subduction (Gutiérrez Alonso et al., 2008, 2011) acted together to cause the generation of the LC–EP calc-alkaline magmas of Iberia in a setting similar to that of typical Cordilleran batholiths (Fig. 3).

In palaeogeographic reconstructions of Pangaea formation during the LC–EP, Iberia is bounded in the west by the Variscan suture and in the east by the Paleotethys Ocean (Cocks and Torsvik, 2006; Stampfli and Kozur, 2006). We suggest that Paleotethys subduction that led to the collision between the Cimmerian terranes (detached from the non-collisional northern margin of Gondwana) and the Eurasian active margin was responsible for the inception of a Paleotethyan magmatic arc in Iberia. We note that the generation of arc-related calc-alkaline magmas in Iberia accounts for a possible link between the Variscan and Cimmerian cycles (Druguet et al., 2014; Pereira et al., 2014). The early stages of Paleotethys Ocean closure were followed by the generation of calc-alkaline arc-related magmas in Iberia, simultaneously with lithosphere-scale bending that produced the accommodation of large continental blocks with associated ductile faulting and the resulting emplacement of large batholiths (Gutierrez-Alonso et al.,

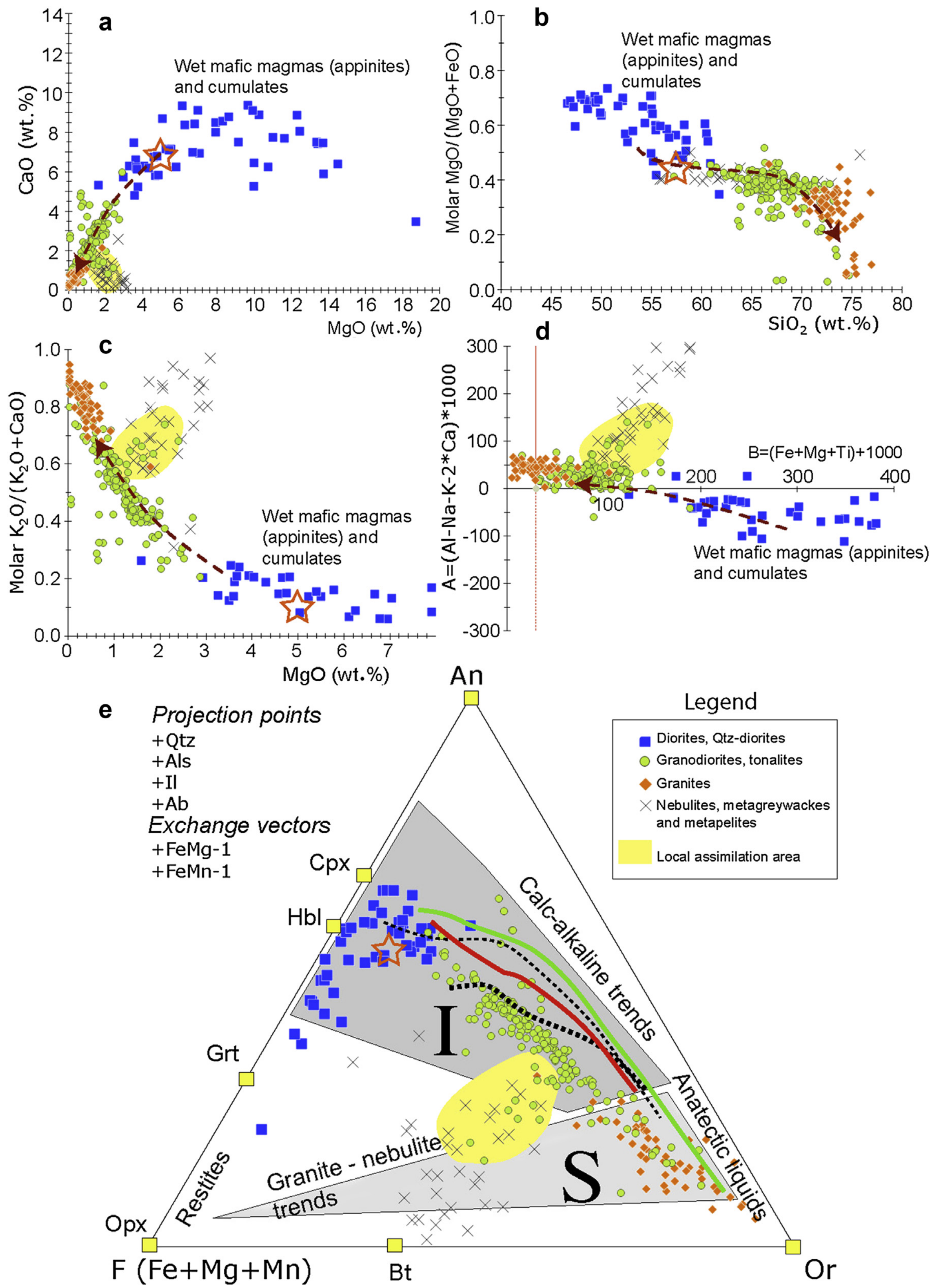

Figure 2. Geochemical diagrams (major elements) showing essential variations of representative granitoids of the Iberian Massif (<315 Ma). Based on geochemical data from Casillas (1989); Ugidos et al. (1997); Bea et al. (1999); López-Plaza and López-Moro (2003); Antunes (2006); Antunes et al. (2008); Orejana et al. (2009) and Díaz Alvarado et al. (2011). Granitoids forming these large Iberian batholiths, classically considered to be late Variscan-late granodiorites of Capdevila et al. (1973) and Castro et al. (2002), are well grouped along curved trends characteristic of Cordilleran batholiths. (a) The CaO-MgO variation diagram can be taken as a proxy of cotectic calc-alkaline evolution trends typically found in arc magmas. The curved trend defines a line of cotectic liquids (LCC) in agreement with experimental melt compositions in calc-alkaline systems. A typical experimental line is traced in the diagrams (dark red dashed line) according to data in Castro (2013). Some of the mafic rocks are cumulates belonging to the calc-alkaline differentiation trend. Other mafic rocks are derived from wet basaltic magmas (appinites), which are commonly associated with the Iberian LC–EP calc-alkaline batholiths and show characteristic and unequivocal arc

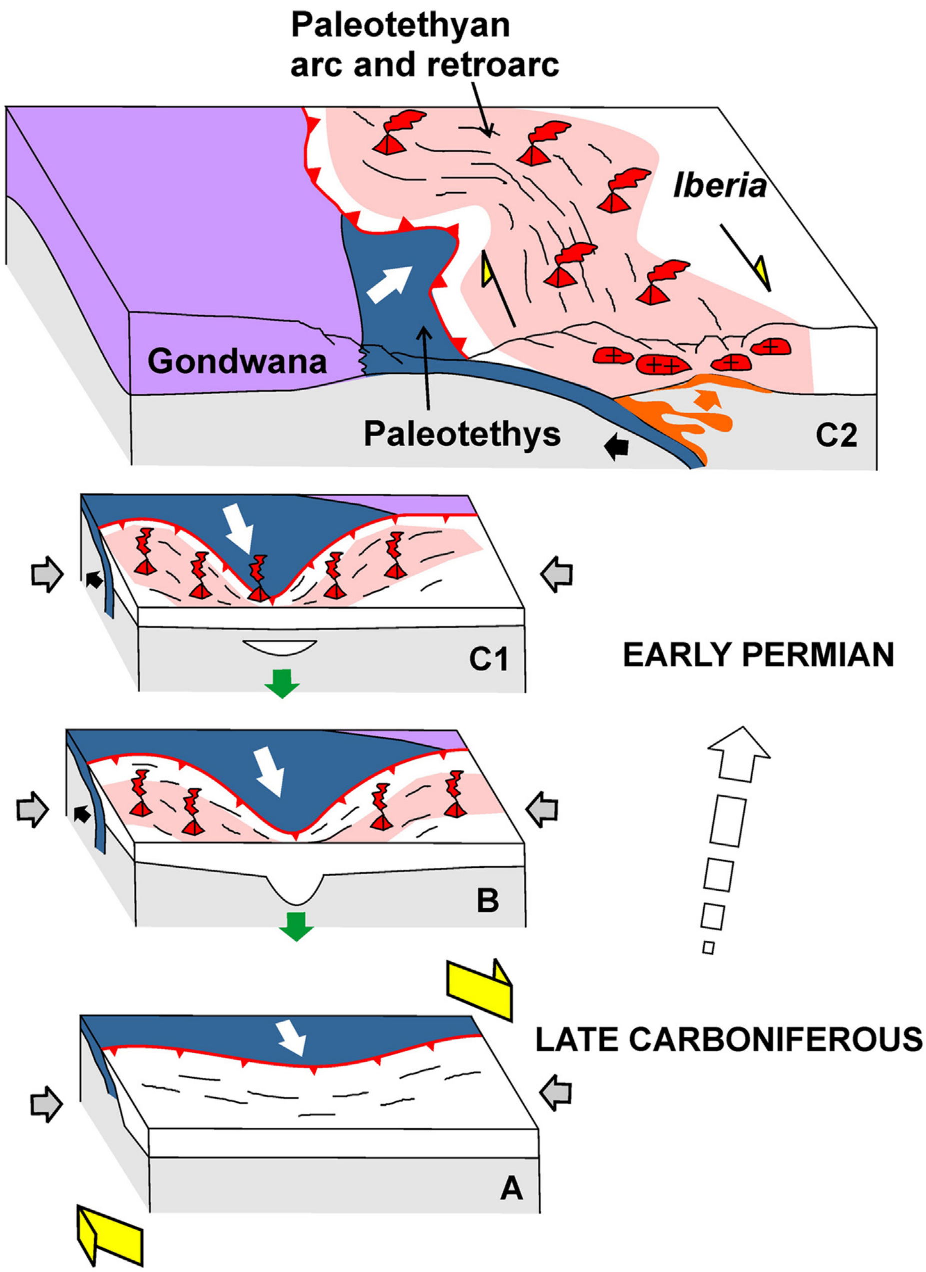

Figure 3. Geodynamic model of the inception of a Paleotethyan arc in Iberia (Adapted from Castro et al., 2013; Johnston et al., 2013; Pereira et al., 2014 and references therein). (A, B, C1) Sequential block diagrams showing the subduction of the Paleotethys oceanic lithosphere (dark-blue), development of the Iberian orocline, the Paleotethyan arc and retroarc (pink), and related strike-slip tectonics. White arrow = approximate direction of convergence between the Paleotethys oceanic lithosphere and the southern limit of the Variscan realm (black lines represent the trace of Variscan structures). Green arrow = lithosphere delamination. Black arrow = slab rollback of the oceanic plate. Grey arrow = orogen-normal principal compressive stress responsible for orocline development. (C2) Block diagrams showing the oceanic-continental subduction zone. Plumes (orange) represent the result of dehydration of the subducted crust, aqueous fluid transport, partial melting, melt extraction and melt emplacement in the form of extrusive volcanics and intrusive plutons (red).

geochemical signatures (Castro et al., 2003). (b) Variation of the molar Mg# shows a plateau region for rocks within the silica range 60–70 wt.%, which is a characteristic feature of Cordilleran granitoid batholiths (e.g., Patagonian batholith: Pankhurst et al., 1999; Herve et al., 2007; Castro et al., 2011; and Sierra Nevada and Peninsular Ranges batholiths: Lee et al., 2006, 2007). (c) Linear and continuous increase of the molar K ratio with decreasing MgO is characteristic of calc-alkaline magma fractionation from a parental diorite precursor. (d) The increase in aluminosity (A parameter: de la Roche, 1978; Debon and Le Fort, 1983) with fractionation is characteristic of calc-alkaline (cafemic) trends. In all diagrams, the effects of assimilation of local country rock (pelitic metasediments) are apparent. Contaminated samples depart from the cotectic trends and point to the composition of pelitic migmatites. (e) Pseudoternary projection into the compositional space F(Fe + Mg + Mn)-Anorthite(An)-Orthoclase(Or). This diagram is used to discriminate between processes of restite unmixing and peritectic restite entrainment that operate in S-type granites (Stevens et al., 2007; Clemens and Stevens, 2012), giving rise to geochemical trends linking anatectic melts and restites (labelled granite-nebulite trends), from processes related to cotectic magma crystallization and fractionation that characterize granodiorite-tonalite batholiths. Most rocks of the calc-alkaline series in the Iberian batholiths plot close to experimental cotectic lines, preferentially close to the low pressure and moderate water cotectic liquids (thick dashed line: Sisson et al., 2005; references for other cotectic lines, red, green and black in Castro, 2013). Several samples tend to deviate from the cotectic line due to local effects of pelitic rock assimilation (Díaz Alvarado et al., 2011). Grey areas in (e) represent the fields of S- and I-type granitoids. Large star represents the probable composition of the parental magma precursor to batholiths (Castro et al., 2013). Characteristic minerals are plotted for reference. Mineral abbreviations after Kretz (1983).

2011; Weil et al., 2012). We propose that the formation of the Iberian LC–EP calc-alkaline batholiths constitutes the earliest magmatic event of the Eurasian active margin. The northward subduction of Paleotethys was responsible for the widespread late Carboniferous calc-alkaline intrusions and volcanism found in the Variscan Alpine–Mediterranean domain (Cortesogno et al., 1998; Stampfli and Borel, 2002). The gradual spread of the Neotethys Ocean and the northward drift of the Cimmerian terranes against the Eurasian active margin during the Permian may have caused the eastward migration of Paleotethys subduction and the associated magmatic arc during the course of the Permian. We further suggest that slab rollback of the Paleotethys oceanic plate during the Permian and Triassic caused the opening of back-arc basins within the Eurasian margin from Austria to China. Later, these back-arc basins were gradually closed during the late Triassic to late Jurassic Cimmerian orogenic cycle (Stampfli and Borel, 2002).

4. Conclusions

LC–EP calc-alkaline batholiths (ca. 315–280 Ma) which formed in Iberia several tens of millions of years from the end of the Rheic Ocean subduction and the time of Gondwana and Laurussia collision (ca. 360 Ma) are unrelated to Variscan orogeny. The magmatism preserves unequivocal subduction-related features, comparable with typical Cordilleran batholiths of the Pacific American active margin. It is proposed that Iberian LC–EP calc-alkaline batholiths were formed during the subduction of the Paleotethys oceanic plate (Pangaea self-subduction) representing the inception of a Paleotethyan arc related to the Eurasian active margin.

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